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INVESTIGATION OF REMOTE CONTROL PROBLEM

By

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REPORT NO. CE57-0348 NOVEMBER 6, 1957

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INVESTIGATION OF REMOTE CONTROL PROBLEM

FINAL REPORT

U. S. - 132

TASK III

Nov. 6, 1957

Author

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Countersigned

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REPORT NO. CE57-0348

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Declassified in Part - Sanitized Copy Approved for Release 2012/02/06 : CIA-RDP78-03172A000200020007-2

ABSTRACT

The feasibility of using a 720 cps carrier voltage for remotely operating a small, highly reliable accessory switch was established. The choice of 720 cps as the operating frequency is not necessarily optimum. Of the switches developed, the thyratron with L-C tuning is the most promising. A thermistor bridge was developed as part of the switch to provide transient immune, unambiguous, self synchronizing operation in response to time-duration coded control signals.

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INTRODUCTION

The purpose of this study was to establish the feasibility of, and develop a working model of, a small size, highly reliable remote control switch [redacted] 25X1

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OPERATIONAL REQUIREMENTS

The requirement imposed on the remote control system and its components are as follows:

1. A very high degree of reliability must be attained.
2. The switch must be of very small physical size and rugged construction.
3. The switch must have a high operating sensitivity consistent with reliable operation.

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4. The switch must be immune to false operation caused by transients on the power line.

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CHOICE OF OPERATING MODE

A study was made of various possible operating modes. Most were not acceptable because they failed to meet one or more of the operational requirements.

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Carrier current operation is considered the only practical means of propagating the signal from the transmitter to the switch while conforming to the operational requirements. It utilizes an existing circuit already common to both the transmitter and switch. It is relatively secure, requiring simple equipment without which unauthorized operation cannot be accomplished. A reasonable transmission efficiency can be attained.

CHOICE OF OPERATING FREQUENCY

Carrier current is used successfully for many commercial applications, principally by utilities for communicating and signaling over long distances via power lines. Frequencies in the range of 50-250 KC are most common for this purpose. Lower frequencies, down through the audio region are also used for control, over shorter distances, of consumer functions such as off peak load water heater control. These systems are operated by superimposing a small magnitude audio frequency voltage on the power frequency and are referred to as low frequency carrier, or ripple, control systems.

The off peak load water heater control system, for example, uses a carrier frequency of 720 cps. This frequency has been found to propagate efficiently in the direction of the power flow through a power system and through distribution transformers. It was selected as a good compromise among several conflicting requirements. It is essential to avoid using odd harmonics of the power line frequency in the interest of reliable operation, since the power frequency has present in it appreciable magnitudes of odd harmonic voltage which may interfere with the operation of the control system.

A lower frequency control signal will propagate through a power transformer with less loss than a higher frequency, but the lower the control frequency, the more difficult it becomes to separate it from the power frequency. This occurs because resonant circuits are used for the control frequency and it becomes more difficult to obtain high enough "Q" in reasonable size inductors to obtain adequate selectivity. A high control frequency is more severely attenuated by capacitive effects along the power line but less energy is absorbed in transformers shunted across the line because of their higher impedance at the higher frequency.

Higher audio frequencies are avoided in a large control system because of their tendency toward creating telephone inductive interference in paralleling telephone lines. This interference maximizes in the 1000-3000 cps region. This is not an important consideration where low frequency carrier is operated over short distances.

In view of the above considerations, along with the availability of adequate performance data on 720 cps systems in the literature, it was decided to conduct the feasibility study at this frequency. It must be emphasized, however, that 720 cps is not to be considered the optimum frequency for this application. A rigorous analysis of low voltage power system characteristics, supported by extensive field testing, would be necessary to determine the optimum control frequency. Such a detailed investigation was considered beyond the scope of this short feasibility study.

As the work progressed and field measurements were made, it became increasingly evident that 720 cps was not the optimum frequency for this application. This will be discussed in detail later in the section on the analysis of the field surveys.

TRANSMITTER

A means of impressing the 720 cps control signal onto the power line was required to determine the 720 cps characteristics of the line and to aid in the development of a suitable switch. A transmitter was assembled from available laboratory components as an expedient. No attempt was made to refine the transmitter beyond its elementary function of exciting the line.

Figure (1) is a functional diagram of the breadboard transmitter. An audio oscillator was used as the 720 cps signal source, which was standardised against the 60 cps line frequency by means of the oscilloscope. The signal voltage was then fed into the 165 watt audio amplifier which had available output impedance of 8, 16 and 32 ohms. Preliminary measurements of the 720 cps impedance of the power lines investigated indicated a range of impedance from 1/3 to 1 1/4 ohms. This low impedance necessitated the use of an additional impedance matching transformer, T_1, to match the output of the amplifier to the lower impedance of the line. This matching transformer had multiple windings, making available a wide range of source impedances.

If the secondary of T_1 were connected directly to the line a destructive amount of 60 cps current would flow through the secondary. This would occur because the source impedance at the secondary of the transformer is extremely low, being the source impedance of the amplifier - 10% of impedance of the output con-

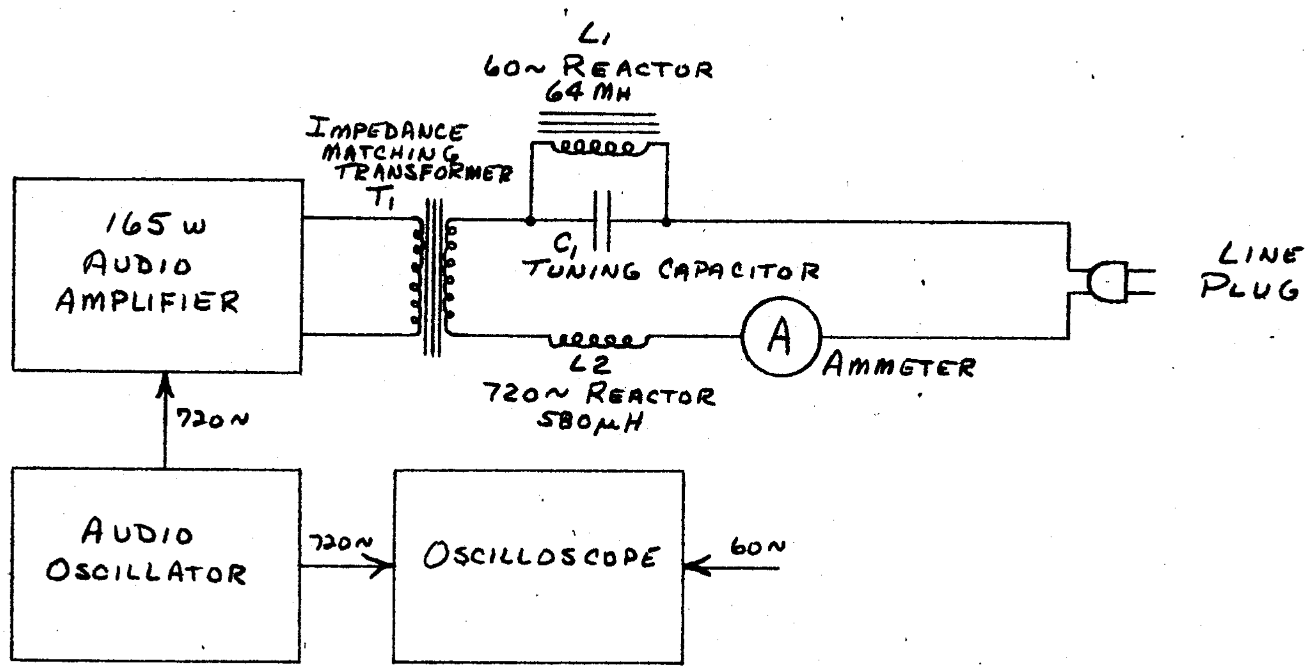


FIGURE 1

FUNCTIONAL DIAGRAM OF TRANSMITTER

nection in use - divided by the impedance ratio of the matching transformer. Therefore some means of blocking the 60 cps current is required without unduly impeding the signal current.

A reactor, L_2, resonated to 720 cps by C_1 forms a low impedance trap which will pass the signal current readily. Much of the 60 cps current is blocked by the reactance of C_1. The value of C_1 is a function of the reactive component of the line impedance, which is also tuned along with the reactance of L_2 and the leakage reactance of the matching transformer. A typical value of C_1 is 54 MFD in the setup used. The 60 cps reactance of 54 MFD is approximately 4.5 ohms, which would pass 25 amps when connected to a 115 volt line. Consequently some means of further reducing the current is required.

The reactor, L_1, tuned to 60 cps by C_1 forms a parallel resonant circuit having high impedance at 60 cps. The resonant impedance is a function of the "Q" of L_1, being Q times the 60 cps reactance of L_1. The 64 MH reactor used has a reactance of approximately 25 ohms and a Q of about 5 at 60 cps, making the resonated impedance some 125 ohms. A 60 cps current of slightly under 1 amp results when the network is connected to a 115V line. The addition of L_1 across C_1 has a negligible effect on the performance of the 720 cps series tuned trap. The 25 ohms inductive reactance across the capacitive reactance of C_1 is tuned out at 720 cps by a slight increase in the value of C_1.

In order to have efficient coupling of the signal into the line the values of L_1 and C_1 must be carefully determined. The series resonated impedance of the combination of L_1 and C_1 should be reasonably small compared to the impedance of the power line to allow the highest signal current into the line for a given VA input to the coupling network. Ideally L_2 should have low inductance and high Q, since the resonated impedance of the series tuned combination is the reactance of L_2 divided by its Q. The reactor used had a reactance of 23 ohms at 720 cps and a Q of 20, making the resonated impedance about 1 ohm. This is not an optimum value since it is 3 times larger than the lowest impedance line measured and results in a substantial reduction in signal current from that which could be obtained with a lower impedance coupling network.

Using a low value of inductance for L_2, although advantageous for reducing losses in the coupling network, has the disadvantage of requiring a very large value for C_1. Since this capacitor is subjected to the line voltage, and being part of a resonant circuit, a high quality paper capacitor is required. This results in a large, heavy capacitor. In a final model of the transmitter, a compromise would probably have to be made between efficiency of coupling and size and weight. The transmitter output coupling network is an area which requires further development in future work.

TRANSMITTER LIMITATIONS

The transmitter has a definite ceiling on its output if it is to fulfill the requirement of operating from any available 60 cps outlet. Branch power circuits found in residences and some commercial buildings are most commonly fused for 15 amps, using #14 conductors. 20 amp circuits are less popular, being used principally for residential kitchens as required by the Underwriter's code. Because of the common use of the 15 amp branch circuit, the r.m.s. sum of the 60 cps current to operate the transmitter and the signal current supplied to the line should not exceed 15 amps to avoid fuse blowing difficulties.

If the fuse cabinet supplying the transmitter operating area is accessible the 15 amp restriction can be removed by changing the appropriate fuse to one of a higher rating. This must be done with care, since the normal overload protection for that circuit will be affected. Normally the transmitter will apply the signal to the line in short pulses of 15 seconds duration or less. A 15 amp fuse of the slow-blowing variety substituted for the ordinary fuse would enable the use of signal currents greater than 15 amps because of its slow response. For example, a 15 amp slow-blow fuse will pass 30 amps for 22 seconds before blowing.

The second transmitter limitation is that imposed upon its size, which may indirectly limit its power. The breadboard transmitter used was by no means portable but only because it was assembled of immediately available components. With careful design and perhaps transistorized circuitry in a final model it seems likely that the current restriction described above will be reached before the transmitter size becomes unreasonably large. Transmitter design was considered beyond the scope of this feasibility investigation and therefore is an area requiring future development.

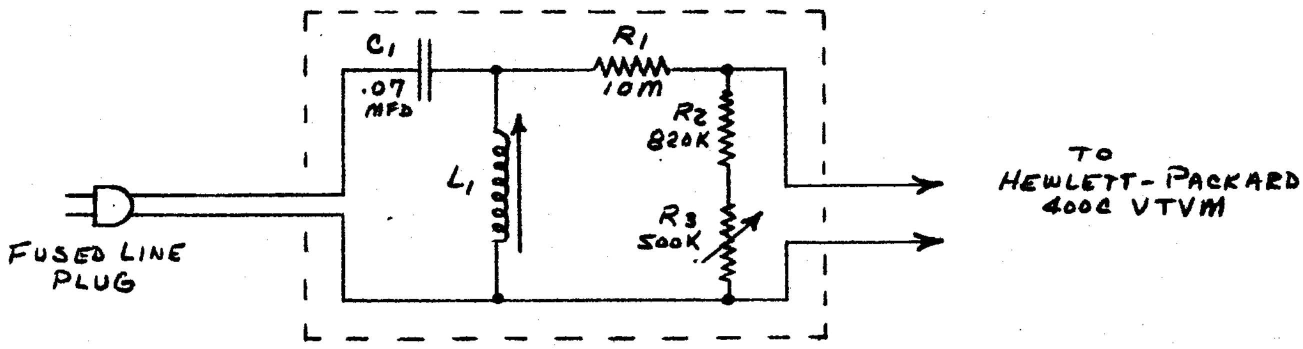
720 cps VOLTMETER

A voltmeter capable of reading only the 720 cps control signal in the presence of the 60 cps power voltage was required to conduct the propagation survey. A tuned 720 band pass filter was constructed for use with a Hewlett-Packard Model 400-C vacuum tube voltmeter. The filter is shown attached to the voltmeter in Photograph (1).

Figure (2) shows the schematic of the filter. C_1 and L_1 form a series resonant circuit which is tuned to 720 cps by adjusting the inductance of L_1.

PHOTOGRAPH 1

720 cps VOLTMETER



L1 - TYPE # 700-H ADJUSTABLE CUP CORE COIL, 125-230 MH
NORTH HILLS ELECTRIC CO., MINEOLA, N.Y.

FIGURE 2
720 CPS VOLTMETER FILTER

A 720 cps voltage, Q times the voltage applied to the filter, appears at the junction of C_1 and L_1. The coil used had a resonated Q of 8 so that a voltage magnification of 8 resulted. To keep the voltmeter direct reading, and to preserve the Q, the 400-C is connected across L_1 through the isolating resistor, R_1. R_2 and R_3 in series form a shunt across the 10 meg input impedance of the 400-C and are used for calibrating the combination of the filter and 400-C so that the meter reads directly in 720 cps volts. The Q of 8 results in adequate suppression of the 60 cps voltage - $57\frac{1}{2}$ db, or a ratio of 1/770. All 720 cps voltages measured during the investigation were made with this filter.

LABORATORY AREA PROPAGATION SURVEY

In order to determine how effectively the 720 cps signal could be propagated over a power distribution system 3 propagation surveys were made, two in a laboratory area and one in a residential area. In all three surveys the transmitter was set up at a selected point and the 720 cps voltage measured at other points on the system by means of the above 720 cps voltmeter. 25X1

Figure (3) shows in simplified form the power distribution in [redacted] Power is brought into the 25X1 yard adjacent to the building at 13.8 Kv. A transformer bank reduces this to 550V for distribution in the building via busses which run vertically in the north end of the building. Transformers located on each of the floors reduce the 550V to lower values for distribution to the loads on that floor.

The power distribution on the 5th floor is shown in Figure (4). Only the two circuits used in the survey are shown, although others of different voltages are available. The bench power circuit is used to supply 115/230V to the benches in the laboratory area. The transformers for this circuit are located about midway on the floor in a small room devoted to electrical equipment

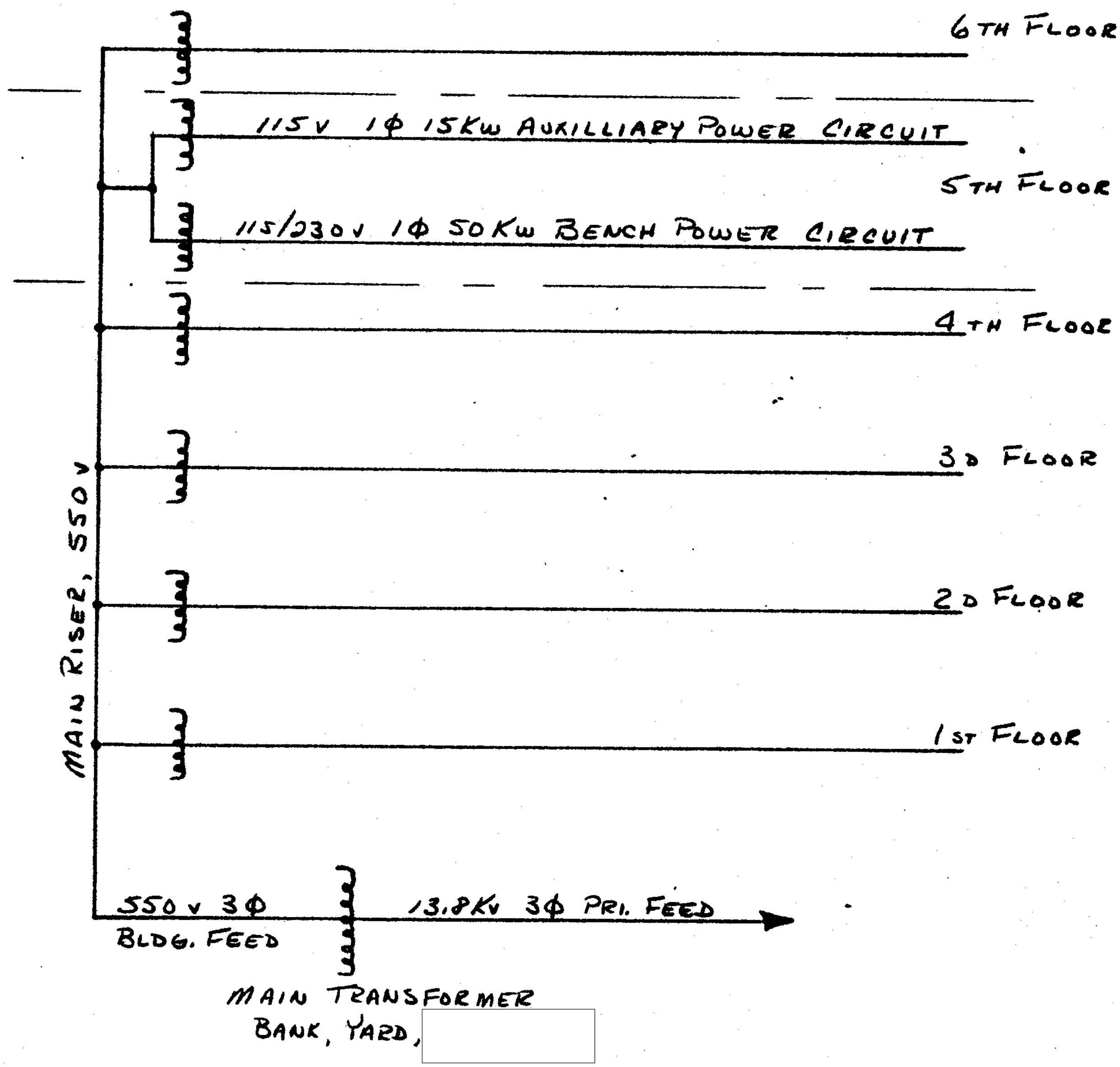


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FIGURE 3

POWER DISTRIBUTION,

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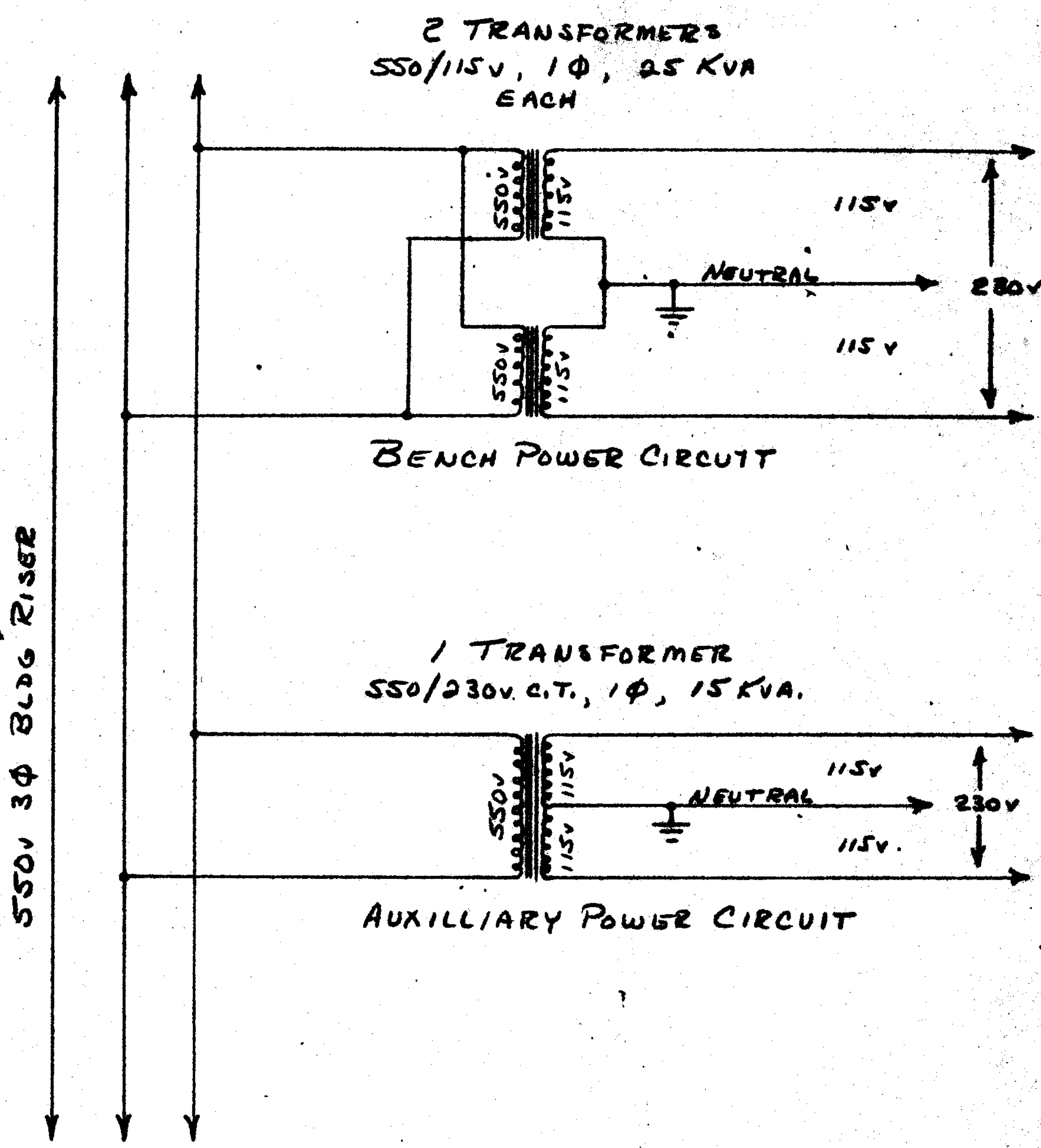

FIGURE 4

POWER DISTRIBUTION - 5TH FLOOR,

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supplying the floor. The 550V to, and the 115/230V from the transformers are carried in open wiring attached to the ceiling. Drops to the individual benches are made with wiring enclosed in conduit. This circuit has the peculiarity of using two independent single phase transformers having their secondaries in series to supply the 115/230V, and their primaries paralleled to accommodate the 550V feed. This results in relatively poor coupling between one 115V line to the other, since the secondaries are not magnetically coupled. Instead, coupling is through the first transformer to the primary of the second, and then through the second to the other side of the line. The effect of this is noted in the discussion of the results of the survey.

The transformer for the auxiliary power circuit is located in the northeast corner of the floor and is connected directly to the 550V risers. The 115/230V is also carried on wiring attached to the ceiling, and is supplied to each of three distribution panels. These panels are about equally spaced along the length of the hall and each serves about 1/3 of the office area. The load on this circuit is relatively light, consisting mainly of electric typewriters, office machines and intercom amplifiers.

The result of the survey along the bench power circuit is shown in Figure (5), a floor plan of the 5th floor. It indicates the points at which the signal voltage was measured, and also the magnitude at that point. The signal was fed to the circuit at the indicated point, with the transmitter connected across one 115V line to neutral. It is evident that the signal voltage decreases rapidly toward the distribution transformer from the feed point. Beyond the transformer the signal remains fairly uniform. In the direction from the feed point away

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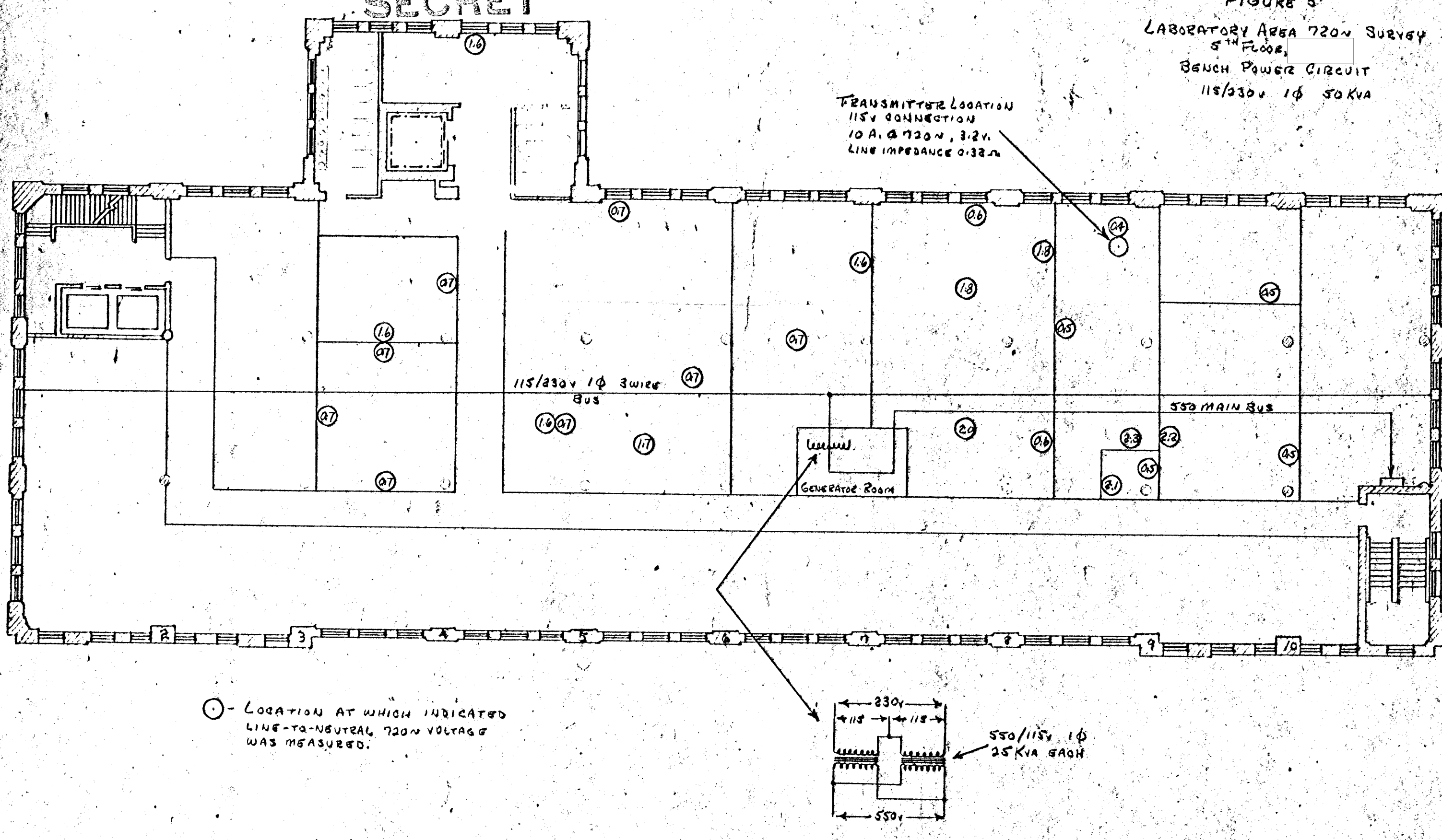
FIGURE 5
LABORATORY AREA 720N SURVEY
5TH FLOOR, [redacted]
BENCH POWER CIRCUIT
115/230v 1φ 50KVA



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SCALE: 1/16" = 1'

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from the transformer the signal also remains reasonably uniform.

The signal measurements fall into two groups - one between 3.2 to 1.6 volts, and another of 0.7 to 0.4 volts. The higher group represents the signal along the 115V to neutral side of the line to which the transmitter is connected. The lower voltages are those appearing on the unexcited side of the line. The use of the two transformers to supply the bench power circuit results in inefficient transfer of the signal from the excited side to the unexcited side. The more normal use of a center tapped transformer would increase the signal in the unexcited side by the autotransformer action of the center tapped secondary.

The result of the signal survey along the auxiliary power circuit is shown in Figure (6). In this case the transmitter was connected to an outlet fed from the distribution panel nearest to the transformer. More uniform signal coverage was obtained on the auxiliary power than on the bench power circuit. Again the signals fall into the high and low groups, indicative of the side of the line to which the voltmeter was connected. Voltages on the excited side range from 3.2 to 2.0 volts while the unexcited side is more uniform in the range of 1.3 to 1.1 volts.

It was noted during the bench power circuit survey that practically no signal was transferred into the auxiliary power circuit. It was suspected that the transmitter power was simply inadequate to drive the unusually stiff 550V feeders found in the lab, and that this was an unusual situation. Later measurements made on a residential distribution system confirmed the difficulty in transferring the signal from the secondary of one transformer to the secondary of a second transformer, both of which are connected to a common feeder. This problem is

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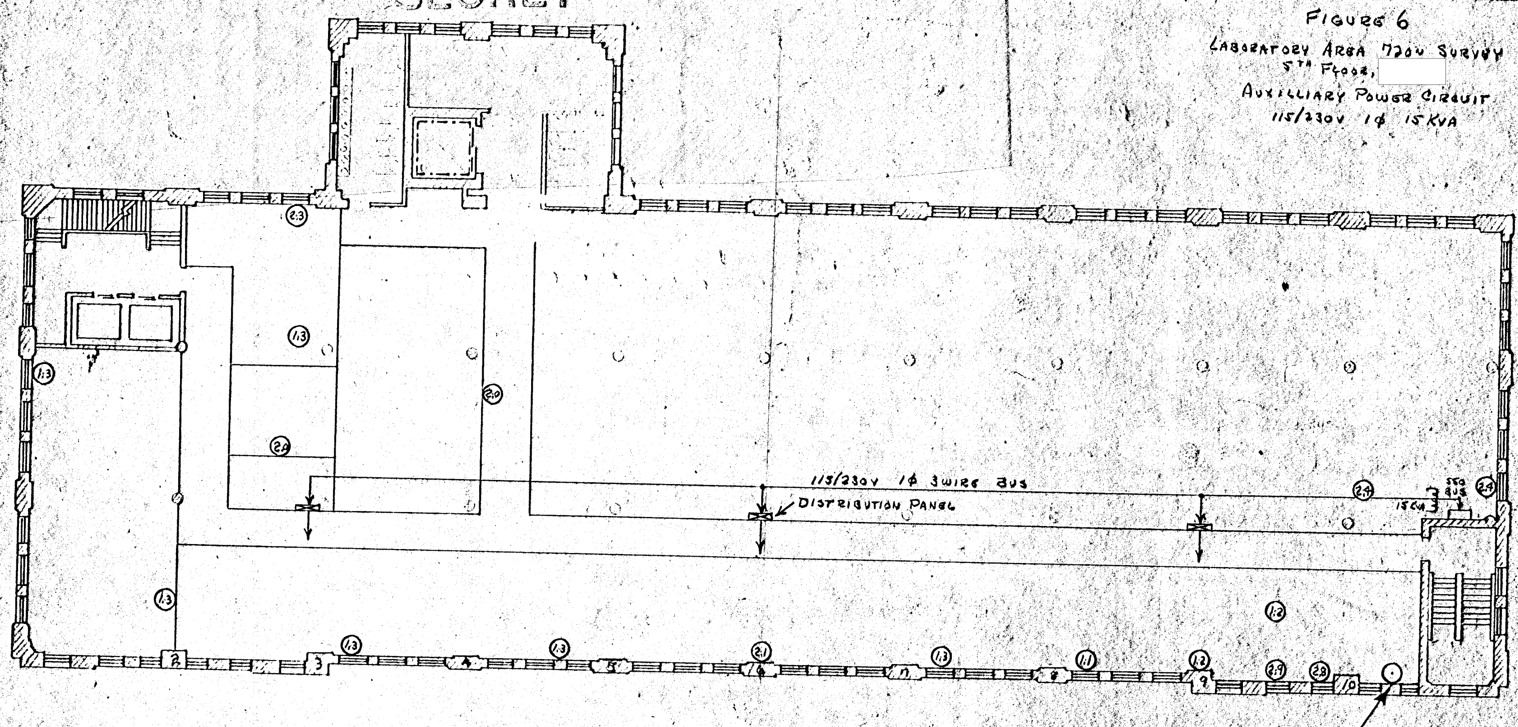
FIGURE 6
LABORATORY AREA 720V SURVEY
5TH FLOOR,
AUXILIARY POWER CIRCUIT
115/230V 1φ 15KVA



⊙ - LOCATION AT WHICH INDICATED LINE-TO-NEUTRAL 720V VOLTAGE WAS MEASURED.

TRANSMITTER LOCATION
115V CONNECTION
5A @ 720V, 3.2V,
LINE IMPEDANCE 0.64Ω

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SCALE: 1/16" = 1'

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treated in the section on the analysis of the surveys.

RESIDENTIAL AREA PROPAGATION SURVEY

The transmitter was set up in a suburban residential area to determine the propagation along a utility distribution system. The area contains typical 2 and 3 bedroom frame dwellings in the $14,000 - $20,000 price range. The street involved is 2 blocks long, dead end, running perpendicular to a main road. The survey was made in the end block, farthest from the main road.

Power is carried into the area along the main road by a 4150V 3 phase feeder. A line to neutral tap of 2300 volts is carried down the street to supply two 25KVA distribution transformers, one serving each block. Their secondaries are not connected together, each transformer supplying only the dwellings in that block. The lines are carried overhead with ordinary utility practice, the primary wires on crossarms and the secondary wires on racks and spools. No information on wire sizes or transformer characteristics was available.

The relative locations of the dwellings and the utility equipment are shown in Figure (7). The transmitter was set up at point A and Photograph (2) shows the setup. Two sets of signal voltage measurements were made at discretely selected residences and the results noted on Figure (7). One set of measurements were made with the transmitter connected line to neutral, giving two values at each of the indicated residences. The higher value is obtained across the excited side of the line, the lower value obtained across the opposite side of the line.

A check was also made with the transmitter connected across the 230V line-to-line wires to determine if this method of excitation would increase the signal. This 230V connection excites both sides of the line simultaneously, resulting in

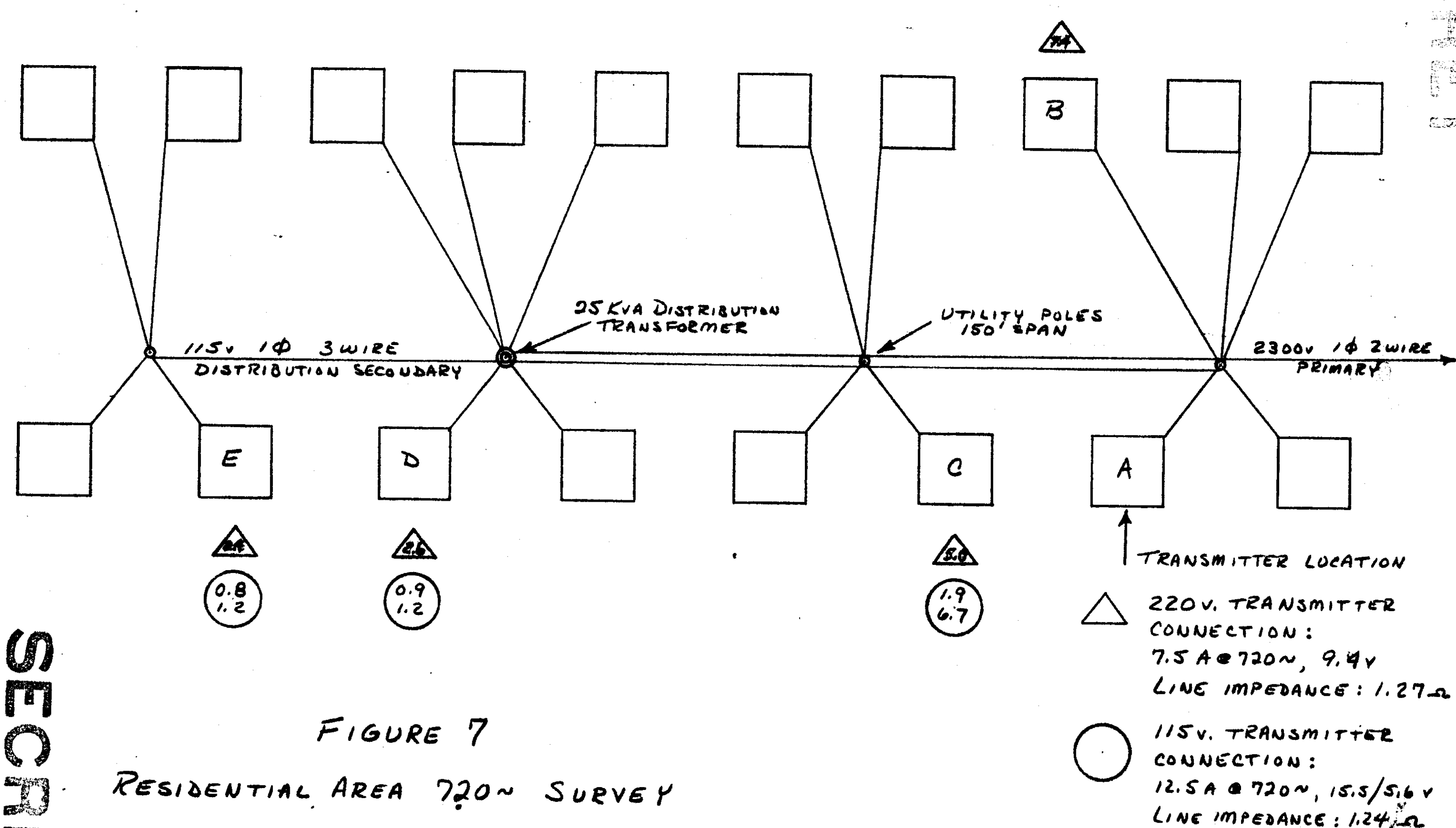
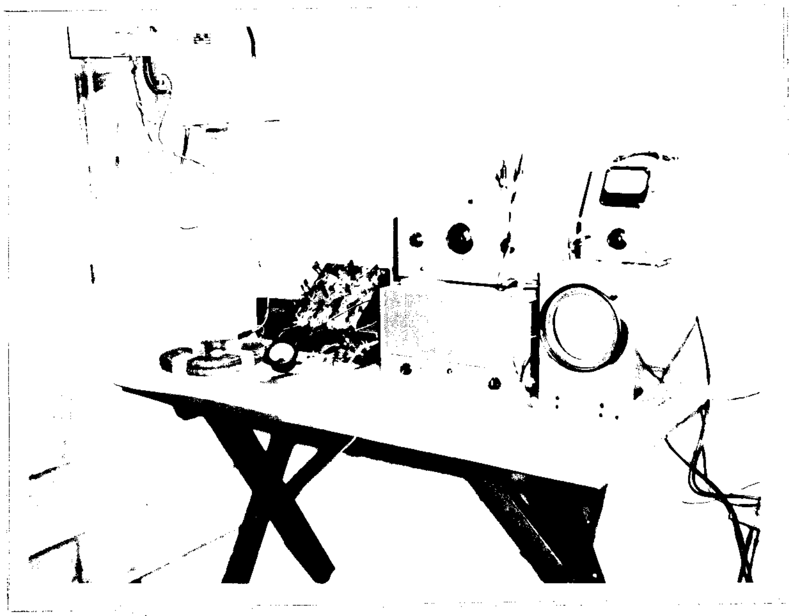


FIGURE 7

RESIDENTIAL AREA 720~ SURVEY



PHOTOGRAPH 2

TRANSMITTER SETUP

equal signal voltage on each side of the line at a given point. A transmitter current of 7.5 amps with the 230 connection produced the same 1.2 volt signal at the end of the line as did a 12.5 amp transmitter current using the 115 volt connection.

With both the 115 and 230 volt transmitter connections there was no trace of the signal at the secondary of the second distribution transformer serving the opposite end of the street.

The normal loads in the power line had only a slight effect on the signal. There was essentially no difference in signal voltage at the end of the line during the high loading periods. Applying an 11 KW load at the transmitter location caused a reduction in signal voltage measured at the transmitter of 7% on the excited side of the line, but raised that of the unexcited side by 5%.

ANALYSIS OF SURVEYS

The residential area distribution system surveyed is shown schematically in Figure 8. The diagram will also apply generally for the bench power and auxiliary power circuits except for the relative locations of the transformer and transmitter. The voltages indicated are those measured with the 230 volt transmitter connection, which was selected for analysis because of the resulting balanced signal conditions on the system. The same general concepts will apply to the system with the 115 volt transmitter connection.

The surveys suggested that the distribution transformer is the dominating influence in determining the signal propagation over a power system. The particular residential transformer in the area surveyed is rated 25 KVA at 230 volts so that its full load current will be 110 amps. According to the literature [1] such a

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1- [redacted]

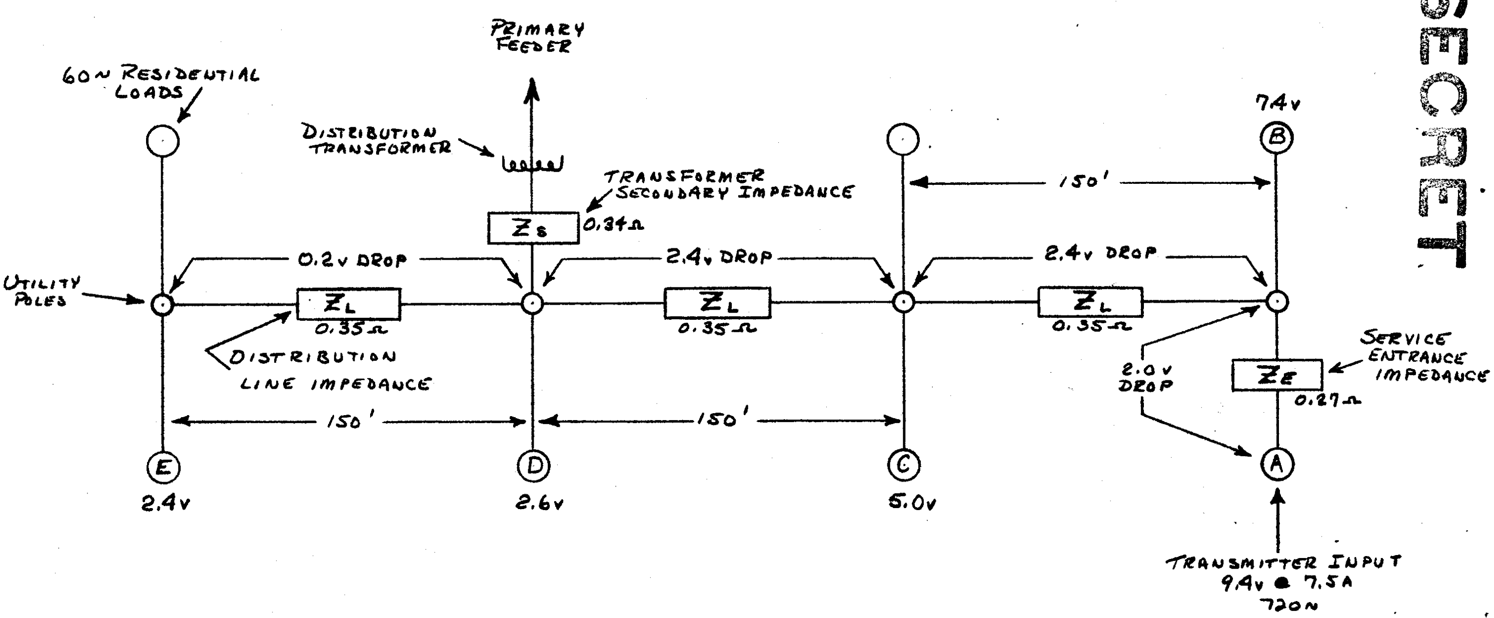


FIGURE 8

SIMPLIFIED SCHEMATIC OF RESIDENTIAL AREA POWER DISTRIBUTION transformer, when energized from a stiff source, may be expected to have 1.5% IR, 1.3% IX and 2.0% IZ regulation. These figures are the percentages that the rated output voltage will drop at full load current as a result of the resistance, reactance and impedance, respectively, of the transformer at 60 cps. These constants may be approximated at 720 cps by applying the ratio of the frequencies. They then become 1.5% IR (the resistance being essentially independent of frequency), 15.6% IX and 16.3% IZ.

Since the IZ is 16.3%, the secondary full load voltage would drop 16.3% or 37.5V, because of the internal impedance of the transformer if it were energized by a stiff 720 cps source. The impedance can then be determined by dividing the full load voltage drop, 37.5 volts, by the full load current of 110 amps. This indicates that the transformer has an internal source impedance of 0.34 ohm at 720 cps. This is also the impedance of the transformer as seen by the transmitter since the primary is shunted by a low impedance feeder. The transmitter must drive the 0.34 ohm internal impedance of the transformer to develop the 720 cps signal voltage across the secondary.

The transformer is fully loaded when the connected load has an impedance of 2 ohms. Allowing for a 100% overload on the transformer during peak load periods, the load impedance would drop to 1 ohm. This is still relatively large compared to the 0.34 ohm transformer secondary impedance. It is evident, therefore, that the transformer is the dominating factor in determining the line conditions at 720 cps, with the 60 cps loads having only a second order effect even under peak load.

If the effect of the connected 60 cps loads are neglected - which it appears reasonable to do at least for light load conditions - more of the properties of the system can be determined. Although negligible at 60 cps, the impedance of the distribution lines and service entrance cannot be neglected at 720 cps. As noted on Figure 8, there was a signal voltage drop of 2 volts in the service entrance and watt-hour meter between the transmitter and the first pole, representing an impedance of 0.27 ohm. Between the first and second poles a voltage drop of 2.4 volts indicates an impedance of 0.35 ohm. A similar impedance between the second and third poles results in another 2.4 volt drop in signal. Of the 9.4 volts generated at the transmitter only 2.6 survives to appear across the transformer secondary as a result of the 720 cps impedance of the line.

There is little loss of signal beyond the transformer, since the 60 cps load impedances are relatively high compared to the 720 cps impedance of the connecting line. This explains the more uniform signal coverage found on the auxiliary power circuit, where all the outlets are on the transmitter side of the transformer. The bench power circuit exhibited a similar high signal loss between the transmitter and transformer for the same reason. More uniform coverage was found beyond the transformer and, in the opposite direction, beyond the transmitter.

The line impedance measured at the transmitter for the 220 volt connection was 1.27 ohms, as determined by dividing the transmitting voltage by the current, The impedance at the same point determined from the voltage measurements indicated on Figure 8 and the calculated transformer impedance is 1.31 ohms.

The conditions for the more normal 115 volt transmitter connection are very similar to those discussed above. The principal difference is the unbalance of signal voltage appearing on the two sides of the line. The signal is transferred to the unexcited side of the line by autotransformer action in the distribution transformer, and by the voltage drop which occurs in the common impedance of the neutral in the region between the transformer and the transmitter. This voltage adds to the autotransformed voltage, so that the voltage on the unexcited side increases toward the transmitter. Beyond the transformer the voltage on the unexcited line is the autotransformed voltage less the line impedance drop. This drop is small however, because the shunt impedance of the 60 cps loads is high compared to the 720 cps impedance of the line. The drop along the excited side of the line beyond the transformer is also small for the same reason.

It was found that with both the 115V and 230V transmitter connections there was no evidence of the signal being present on the secondary of the second distribution transformer on the street. The literature on the use of low frequency carrier control systems indicates that the control signal can be propagated with ease in the same direction as the power flow in a system. The surveys made indicated that it is difficult to propagate the signal in the direction opposite to the power flow, or "upstream," with any reasonable size transmitter.

It was found that the 25 KVA transformer had a secondary impedance of 0.34 ohm. When this impedance is referred to the primary by multiplying it by the square of the primary to secondary voltage ratio, 100, it is found that the primary impedance is 34 ohms. This becomes the driving impedance with which the transformer excites the primary feed line when its secondary is driven by the transmitter. No information was available on the source impedance of the primary feeder, but it can be assumed to be low. The 60 cps primary impedance of the transformer under peak loading is 100 ohms. The two transformers on the feeder represent a load of 50 ohms. To maintain a reasonable 60 cps voltage regulation of say 5%, the feeder source impedance would be 2 ohms. This 2 ohms is the load impedance that must be driven by the 34 ohms source impedance at 720 cps. It becomes apparent that it is difficult to transfer 720 cps power into the feeder because of the large impedance mismatch involved.

The power delivered to the secondary of the distribution transformer was only a small part of that delivered into the line by the transmitter. Because of the impedance drop in the line only 2.6V of the 9.4V at the transmitter appeared at the transformer. On a 230V basis, the voltage appearing on the primary feeder would be 2/34 of the 2.6V across the secondary, or only 0.15V. Allowing for a 20% loss, which the literature indicates is typical when propagating downstream, only about 0.12 volts would be delivered to the secondary of the second transformer on the street. Only about half of this voltage would appear across each side of the secondary.

The 720 cps voltmeter used had a selectivity such that when an input of 115V 60 cps was applied a reading of 0.15V resulted. Therefore the minimum 720 cps voltage that could be read would have to be somewhat above this value. Since the voltmeter was connected line to neutral when checking on the secondary of the second transformer, the anticipated $\frac{0.12}{2}$ volts could not be confirmed. It seems reasonable to conclude, however, that such a small signal would be inadequate for control for this application.

Several other conclusions can be drawn from the above discussion. Perhaps the most significant is that the exploratory frequency of 720 cps is not necessarily the optimum for the application. It is apparent that a lower frequency would improve the propagation of the signal along the 60 cps system by reducing the reactance of the distribution lines and transformers. The use of a lower frequency may enable the propagation of a useful signal through two transformers within the size limitations of the transmitter. Additional tests must be performed to evaluate the possible benefits of a lower frequency.

Conversely, if there is no urgent requirement for propagating through two transformers, a higher frequency could be used and would suffer less attenuation caused by the shunting reactance of the transformer. A smaller transmitter would then be required, but would be useful only on the secondary load circuits of a given transformer. A higher frequency would make possible the use of higher Q reactors of smaller size with correspondingly higher voltage magnification, producing additional stable sensitivity in the switch. This factor would contribute toward reducing the size of the transmitter required.

It is advantageous to install the transmitter and the switch along the line on the same side of the transformer, and preferably with the transmitter between the switch and the transformer. This arrangement produces the highest signal at the switch because the shunt loading of the transformer is reduced by the reactance of the line between the transmitter and the transformer. The signal voltage along the line in the direction away from the transmitter and transformer then suffers only slight attenuation and remains more uniform over a greater distance. This situation is illustrated by the survey along the auxiliary power circuit.

The most adverse situation encountered in the surveys was that of the bench power circuit. This circuit is unusual in the use of two separate transformers having their secondaries connected in series to supply the 115/230V. As a result there is almost complete absence of autotransformer action for the signal. The secondaries are coupled only through the paralleled primaries, and as discussed previously, the resulting transfer of signal is very small. The unenergized side of the line received its share of the signal principally through the common impedance of the neutral wire. Even under these poor conditions a reasonably adequate signal was found over the operating area.

Although certain configurations of transmitter, transformer and switch may have propagation advantages, the design goal for the system must be to secure satisfactory performance under the most adverse condition. It would be a serious handicap to the application if each of the components had to be placed in a prescribed relation with respect to the transformer.

TG-1 LOAD SWITCH

A 720 cps off peak load water heater switch, [redacted] was obtained to 25X1
evaluate its operation and determine its usefulness for the application. The load switch consists of two main components - a 720 cps sensitive relay, and a power relay with a time delay. The sensitive relay consists of a magnetically actuated mercury switch, an actuating coil on a magnetic core, and a tuning capacitor to resonate the coil to 720 cps. The mercury switch and core is shown in Photograph(3A.) The series combination of the coil and capacitor is connected across the line and the capacitor limits the 60 cps current flowing in the coil to a sufficiently low value which will not actuate the mercury switch. When a 720 cps signal of about 1 volt appears on the line, a high current flows in the coil because of its low series resonated impedance and the mercury switch closes.

Closure of the mercury switch applies power to a thermostatic element which deflects as it heats. This deflection is used, through a mechanical latching toggle action, to tilt a power mercury switch. The toggle action is employed to maintain the power mercury switch in its tilted attitude after power is removed from the bimetal, and, in combination with the bimetal, to obtain a positive sequential action. The means of obtaining this sequential action in the TG-1 switch, while interesting in itself, is of no direct value to the application because of its relatively large size. However, its operational functions were deemed to have great merit.

Because of the use of the time delay introduced by the thermostatic bimetal the TG-1 is totally immune to any short transient disturbance on the line. A control signal of from 3 to 12 seconds duration is required to turn the switch on. During this time the power mercury switch is tilted to its on position by the deflection of the bimetal and then restrained in the on position by the latching action of the toggle. Upon removal of the control signal the bimetal is de-energized and returns to its normal undeflected position in about 1 minute.

A control signal of from 15 to 36 seconds duration is required to turn the switch off. During this time the bimetal is energized and, because of the longer time, deflects further than it did during the on period. This increased deflection then releases the toggle and the power mercury switch is returned to its off position. A cooling period of about 3 minutes is required after removal of the control signal before the bimetal is ready to repeat its action.

This action results in three features desirable for the application. The time constant of the bimetal immunizes the switch to disturbing transients. The selective time response of the bimetal and toggle produce unambiguous operation as a function of the control signal duration. A positive, self synchronizing action is obtained from the unit.

THERMISTOR BRIDGE

The large size of the bimetal-toggle-mercury switch of the TG-1 load switch prevented their adaptation for the application. Their performance however, was so attractive that an investigation was made to determine a means of obtaining similar action by electrical means. Ordinary thermal delay relays were ruled out because of their fragility and poor reliability. The investigation quickly narrowed down to thermistors because of their small size and high reliability.

Thermistors are temperature sensitive resisters having a high negative temperature coefficient of resistance. As their temperature increases, the resistance decreases. By varying the composition during manufacture and by the use of various shapes, wide control of their properties is possible. The characteristics are stable and uniform over wide operating ranges.

The negative resistance property of a thermistor may be employed to generate stable timing circuits. When a voltage is applied to a thermistor and a resistor in series, a current will flow which is determined by the impressed voltage and total circuit resistance. If the voltage is high enough, some heat will be generated in the thermistor. This will lower its resistance and more current will flow. This effect is cumulative, the additional heating producing more current. The process continues until the thermistor reaches the maximum temperature possible for the amount of power available in the circuit. Equilibrium is then established.

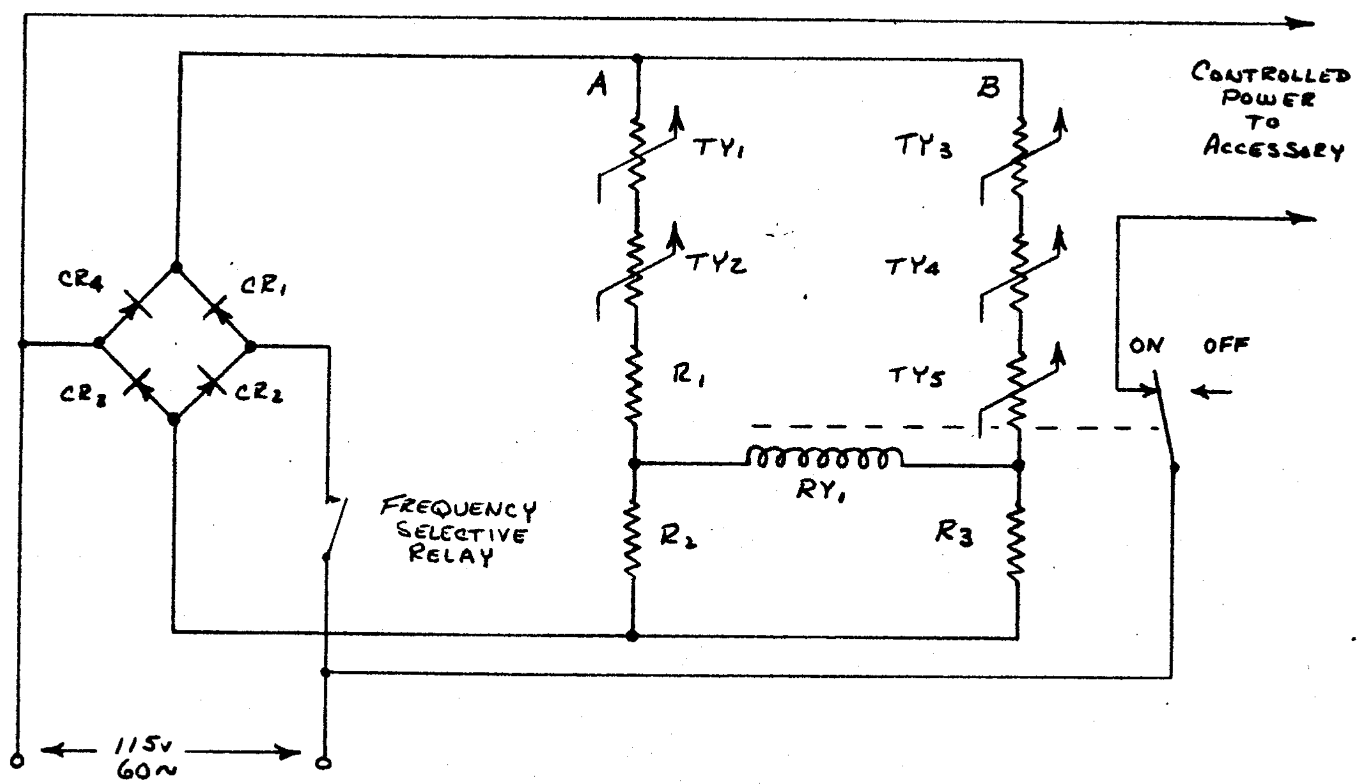
The thermistor has a finite mass, so that it takes time to be heated to its maximum value. The time required is a function of the mass, the applied voltage, and the value of series resistance. By a suitable choice among these parameters it is possible to produce a wide variety of delay times.

A thermistor bridge circuit was developed in which these parameters were adjusted to duplicate the performance of the TG-1 load switch. The bridge was developed using empirical methods and, while it functions well, it is not necessarily an optimum design. It was developed to establish the feasibility of using thermistors for the purpose. The bridge involves so many dependent variables that the use of an analog computer would be advantageous in optimizing the design. Having established the feasibility, the optimization of the bridge was considered beyond the scope of this preliminary work.

The circuit of the thermistor bridge is shown in Figure (9). Two legs of the bridge contain resistors only, R_2 and R_3. The remaining two legs are made up either of a resistor and two thermistors, or of three thermistors. A rectifier energizes the bridge with unfiltered rectified AC, required because of the use of a DC relay at the output of the bridge. The bridge output is a differential current which flows through the relay coil.

A polarized D-C relay with magnetic latching is used. This relay has two stable positions. Coil current of one polarity only can cause the armature to transfer from a given fixed position to the other. Opposite polarity is then required to return the armature to the original position. The function of the relay is analagous to the toggle of the TG-1 switch.

At the moment the bridge is energized the current flowing in each branch of the bridge is determined by the rectifier output voltage, 104V D.C. for 115V input. and the cold resistance of the thermistors, about 1000 ohms each. This initial



CR1, CR2, CR3, CR4	1N93 GERMANIUM DIODES	
TY1, TY3	[redacted] THERMISTORS	25X1
TY2, TY4, TY5	THERMISTORS	
R1	140 Ω 1 WATT RESISTOR	
R2	390 Ω 2 WATT RESISTOR	
R3	730 Ω 2 WATT RESISTOR	
RY1	SIGMA TYPE 73JSZ RELAY, 7000 Ω COIL 1½ A. SILVER CONTACTS	

FIGURE 9

THERMISTOR BRIDGE

current heats the thermistors and their resistance decreases, increasing the current. However, since there are 2 thermistors in side A and 3 in side B, the current is higher initially in side A and increases at a faster rate than side B. These currents flow through R_2 and R_3 and divide between them so that the difference current flows through the relay coil. When the current in branch A is greater, the net current flow through the relay coil causes the relay armature to close in one direction.

As the thermistors continue to heat, the current in side B becomes sufficiently large so that the net current through the relay is reversed. This causes the relay armature to transfer to the opposite position. The thermistor resistance decreases to about 20 ohms when they reach equilibrium. The final current is determined by the resistors in each leg of the bridge. About 20 watts are dissipated in the bridge components at equilibrium.

About 2 seconds are required after the bridge is first energized to actuate the relay to the position corresponding to turning on the load. At this time the excitation may be removed and the relay will remain in its on condition because of the magnetic latching feature. If the bridge remains energized, the relay will transfer to the opposite, of off, position in about 10 seconds. The excitation may then be removed, leaving the relay in the off position.

The self synchronizing feature of the TG-1 load switch is duplicated in the thermistor bridge. If the position of the relay armature is unknown, applying excitation to the bridge for the 10 second period will always cause the relay to go to the off position. If the relay was in the on position previously, it will simply transfer to the off position in the normal manner. If the relay was off previously, it will first turn on after 2 seconds, remain on momentarily, and then transfer to the off position. Thus the relay can always be brought to the desired position even though its previous position is unknown.

An interval is required between operating cycles to allow the thermistors to return to ambient temperature. About 5 minutes are required after the off cycle before the relay can be turned on again. The relay can however be turned off immediately, since this phase of the operation does not require that the thermistors cool. The bridge operating time will be influenced slightly by variation in ambient temperature. The power input to the bridge was deliberately made relatively high to produce a thermistor equilibrium temperature adequately above the highest anticipated ambient temperature to improve the stability.

MERCURY ACCESSORY SWITCH

A breadboard model of the accessory switch was assembled using the frequency selective relay components taken from the TG-1 load switch. The use of the magnetically actuated mercury switch appeared to have the advantage of simplicity and potentially reliable operation. The disadvantages are the relative fragility and position sensitivity of the glass enclosed mercury switch.

Figure 10 shows the schematic of the switch. The coil of the magnetic assembly, L_1, shown in Photograph (3A), is resonated to 720 cps by C_1. The impedance of C_1 is 1800 ohms at 60 cps, so that the resulting 60 cps current in the coil is not large enough to actuate the magnetic mercury switch SW_1. However, at 720 cps the resonant impedance is 11 ohms, so that only 1 volt is required to cause the mercury switch to close. It was found that when the switch was

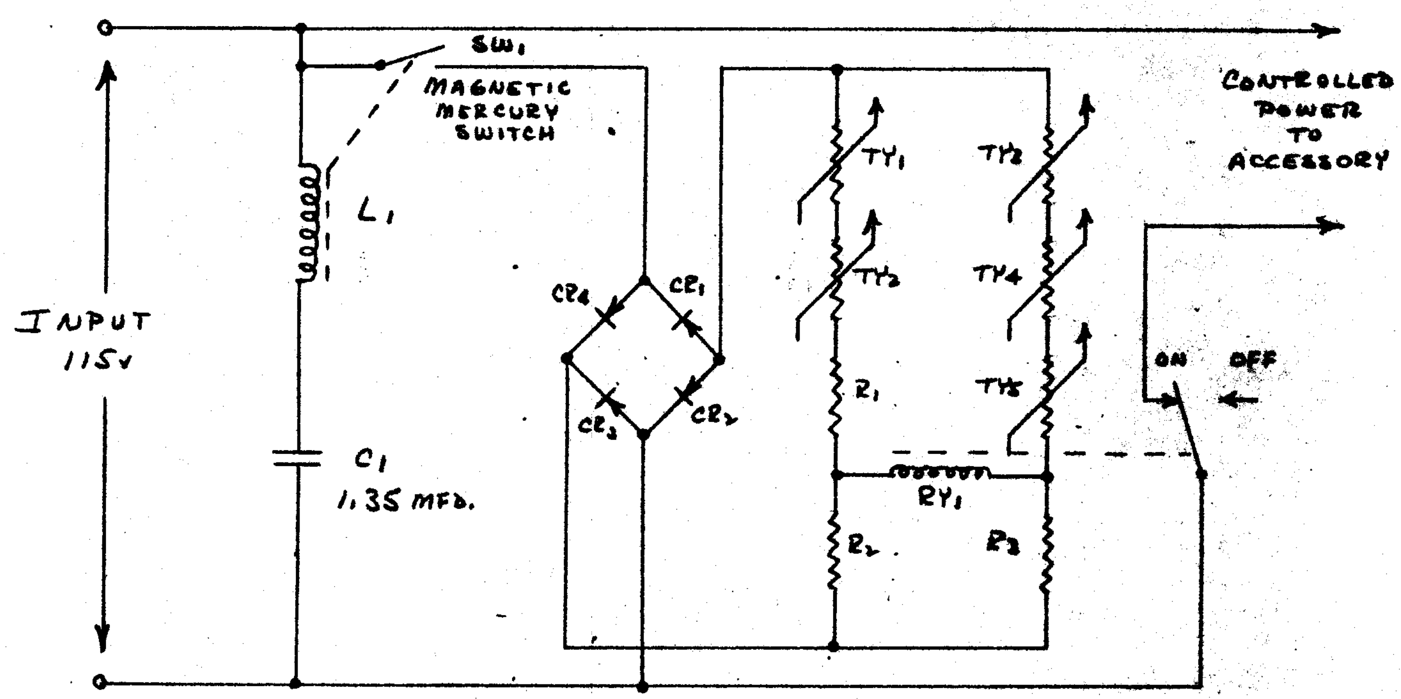
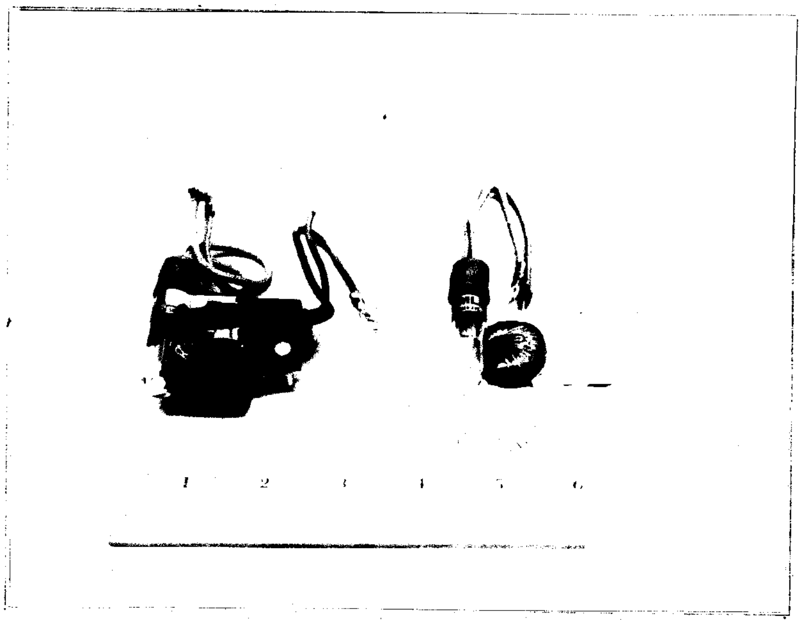


FIGURE 10

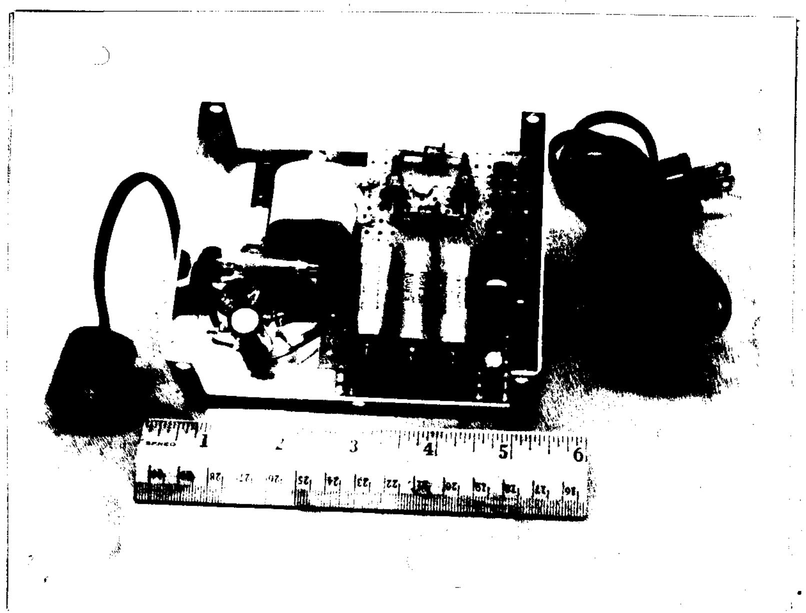
MERCURY ACCESSORY SWITCH



A B

PHOTOGRAPH 3

MERCURY SWITCH SENSITIVE RELAY



PHOTOGRAPH 4

MERCURY ACCESSORY SWITCH

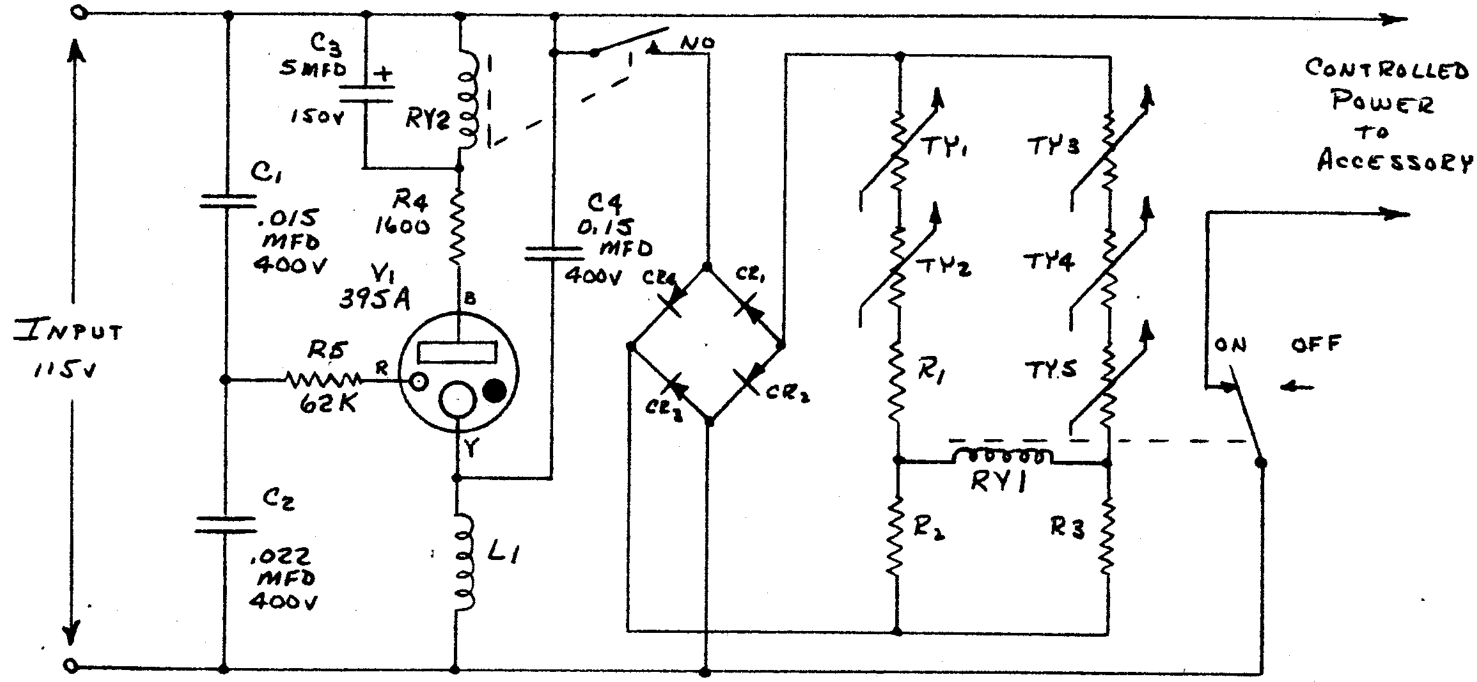
packaged in an aluminum box as shown in Photograph 4, the Q of the coil was reduced from 16.5 to 12 because of the effect of the aluminum of the box near the coil. As a result, the packaged switch required 1.3 volts at 720 cps to close the mercury switch. When the mercury switch closes, the 115V 60 cps is applied to the rectifiers which energize the thermistor bridge to functions as described previously.

The magnetic structure as used in the TG-1 switch is too large to allow packaging in a compact assembly. An attempt was made to reduce its size by employing a more efficient magnetic circuit using a small "C" core. Several trials produced the smaller assembly shown in Photograph 3B. While the resulting sensitivity was not quite equal to the original, it did serve to indicate the feasibility of reducing the size. Additional development could have produced a smaller assembly having at least equal, or perhaps even greater sensitivity but it became increasingly apparent that the mercury switch approach was far from ideal for the application.

During the work with the mercury switches their fragility became more obvious. Two were broken during handling while constructing the packaged accessory switch. Although first appearing attractive because of their simplicity, the lack of ruggedness and their position sensitivity, prevented the mercury switches from meeting the requirements of this application.

THYRATRON ACCESSORY SWITCH

The thyratron accessory switch uses a cold cathode thyratron in the circuit shown in Figure 11. The thyratron is connected in series with a relay coil, RY1, and an inductor, L_1, across the 115V 60 cps line. A fraction of the 115 volts,



L_1	300 MH, PART NO. MP-206-24-B TOROID COMMUNICATION ACCESSORIES CO., LEE'S SUMMIT, MO.
RY2	POTTER AND BRUMFIELD TYPE PW5LS, 10,000 Ω COIL.

FIGURE 11

THYRATRON ACCESSORY SWITCH

determined by the reactance divider C_1 and C_2, is applied to the trigger electrode to bias the thyratron to slightly less than the breakdown bias.

A capacitor, C_4, resonates the inductor to 720 cps. When a 720 cps voltage appears on the line, "Q" times this voltage is developed across the inductor. This voltage appears between the cathode and trigger of the thyratron and adds to the bias already on the trigger. The thyratron then breaks down and continues to conduct while the 720 cps voltage is present.

Current to the thyratron passes through the relay coil, causing its contacts to close and apply power to the rectifier and thermistor bridge. The bridge then performs as described previously to turn the accessory on or off. Since the thyratron conducts only on alternate half cycles of the 60 cps, the capacitor C_3 is required to maintain current in the relay coil. This capacitor is charged during the conducting half cycles and supplies the current necessary to hold the relay closed during the non-conducting half cycles. The resistor R_4 limits the charging current of C_3.

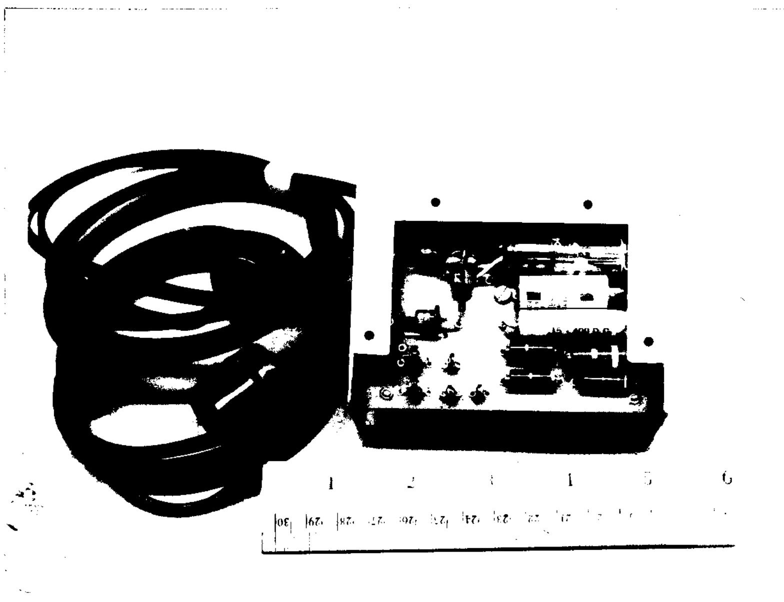
A reactance voltage divider, C_1 and C_2, was used to avoid the stand-by power dissipation that would result from the use of resistors. The stand-by line current of the receiver is entirely reactive so that the switch consumes no true power. The 60 cps stand-by line impedance of the thyratron receiver is 20,000 ohms capacitive, causing a 0.006 amp current at essentially zero power factor. The line burden is 0.7 volt-amps reactive. The absence of any true power dissipation makes the presence of the device impossible to detect by watt-hour meter observations. The switch cannot be detected by a resistance measurement across the line since DC is blocked by the capacitive divider and by C_4. The capacitive input of the switch would add little to the existing capacity of the wiring across which it is installed, making difficult the detection by capacity measurements. A high degree of security exists in the thyratron switch.

The type 395-A thyratron was selected because of its small size, high sensitivity and ruggedness. It is a JAN approved type and has a 1000G shock and vibration rating. Its small dimensions are well adapted to miniaturization of the switch.

A laboratory sample thyratron switch was constructed and is shown in Photograph 5. While made conveniently small, no attempt was made to miniaturize it. The volume required could be reduced substantially, perhaps by 50%, by judicious use of miniaturized components.

This switch has a sensitivity of 0.8 volts, determined by the bias applied to the thyratron and by the Q of L_1. The bias of about 50 volts was selected as being well below the lowest trigger breakdown voltage of the 6 samples available for test. This bias could probably be increased to yield greater sensitivity but more information is required on the statistical variation of the trigger voltage for a larger quantity of thyratrons. A higher Q for L_1 would result in greater sensitivity, but at the expense of larger physical size. The reactor used was a 1" dia x 1/2" high quality toroid having a resonated Q of 20, yielding a signal magnification of the same value. Greater magnification can be obtained with the higher Q of a larger reactor.

The thyratron switch was tested on both the lab power systems and the residential system. Good operation was attained at the maximum available distance of 250' in the laboratory power circuit and at the maximum distance available, 450', on the



PHOTOGRAPH 5

THYRATRON ACCESSORY SWITCH

secondary of the residential circuit. An interference check was made on the switch by operating it from the same outlet to which was connected, in turn, an electric shaver and a kitchen mixer. Both of these are notorius interference generators, the ones used producing snow on a TV set during the test. The switch functioned normally in the proximity of this interference .

Although the thyratron switch uses more components than the mercury switch, the reliability can be made very high by the use of top quality components. The 395-A thyratron is rated as a reliable type and has found widespread use in telephone service where reliability is important.

RESONANT RELAY ACCESSORY SWITCH

A sample of a Frahm resonant reed relay was evaluated as the sensitive frequency selective element. The relay consists of a mechanically resonant reed placed in the field of an electromagnet. When the electromagnet is energized with an A-C voltage of a frequency at which the reed is resonant, the reed is set to vibrating. Contacts actuated by the reed are then closed intermittently by the vibration of the reed. The rate of contact closure is equal to the exciting frequency.

The resonant reed relay has two principle advantages - high sensitivity and sharp selectivity. The reed is excited at its resonance and very little driving power is required. The mechanical Q of the reed is very high, resulting in a very narrow frequency range over which the reed will respond. Both sensitivity and selectivity are stable over a wide temperature range.

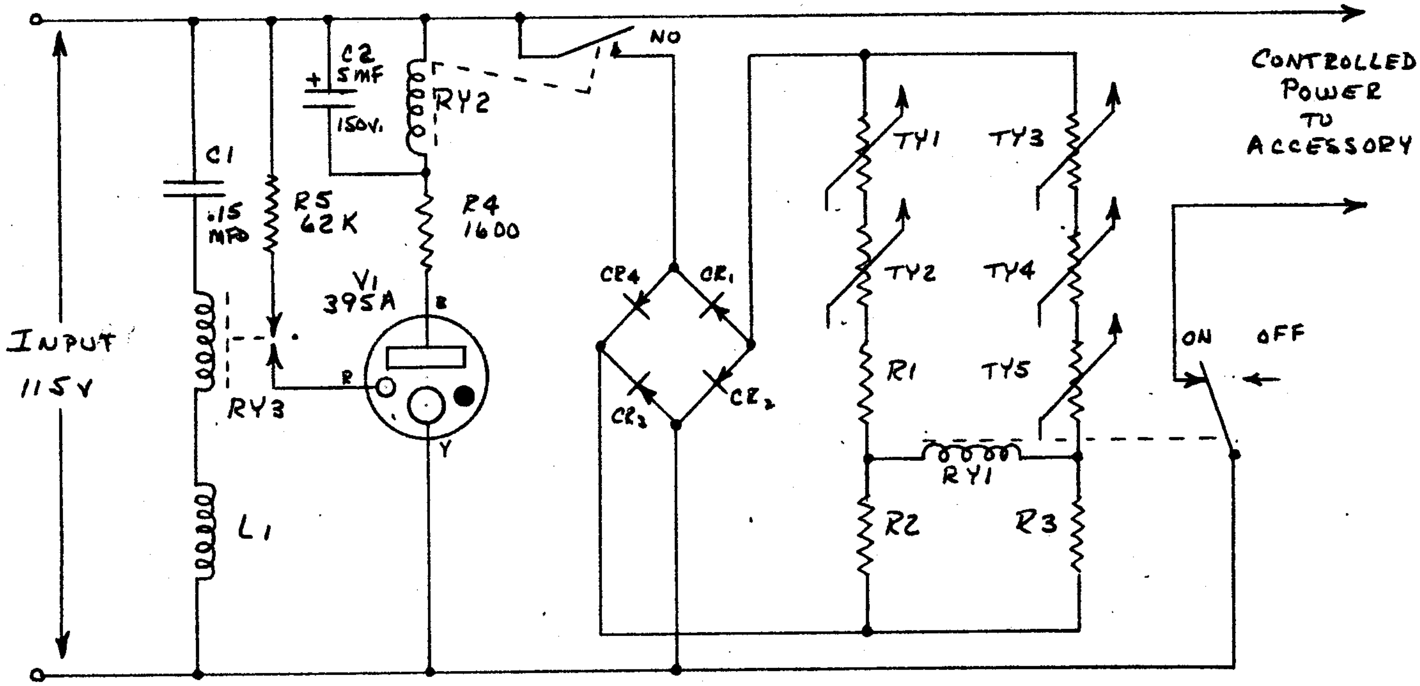
The disadvantage of the relay is the low duty intermittent contact produced. The contact dwell time is 5% or less, and the maximum peak contact loading is only 200 Mw. As a result it is necessary to employ an auxiliary relay or thyratron to obtain continuity.

The Frahm RR-10 resonant relay was originated for airborne operation and is MIL approved. It is small - 1/2" dia x 2" long - and rugged, meeting 100 g vibration and acceleration requirements. Those used were of a standard variety having a resonant frequency of 716 cps and a coil impedance of 16 ohms. A 0.08V signal on the coil caused the contacts to close intermittently.

The difficulty encountered with the resonant relay was in coupling the low coil impedance to the power line. A large coupling capacitor between the coil and line is required to preserve the high sensitivity of the relay. This large capacitor causes an excessive 60 cps current through the coil, resulting in overheating of the coil. A compromise was arrived at in which a 720 cps series resonated trap was connected in series with the relay coil across the line, as shown in Figure 12.

The series trap has a resonated impedance 65 ohms and reduced the effective sensitivity of the combination to 0.3V. The 0.15 capacitor has a reactance of 20,000 ohms at 60 cps, effectively blocking the 60 cps current from the relay coil. It has since been determined that there is available another relay similar in all respects to the RR-10 except that the coil impedance is 1000 ohms. This coil could be connected directly to the line through a 0.25 MFD capacitor to give a 0.16V sensitivity.

The resonant relay switch was not carried beyond the simple breadboard stage because of the difficulty of coupling the coil of the available sample to the line. The circuit used for the breadboard is shown in Figure 12. A 395-A thyratron



L_1	300 MH. PART NO. MP-206-24-B TOROID COMMUNICATION ACCESSORIES CO., LEE'S SUMMIT, MO.
RY2	POTTER AND BRUMFIELD TYPE PW5LS, 10,000 Ω COIL
RY3	TYPE RR-10 RESONANT RELAY, 716.1 ~, 12.5Ω D-C COIL JAMES G. BIDDLE CO., PHILADELPHIA, PA.

FIGURE 12

RESONANT RELAY ACCESSORY SWITCH

was used to convert the intermittent contact of the resonant relay to a sustained contact to actuate the thermistor bridge. The momentary closure of the resonant relay contacts applies the 115 volts to the trigger of the thyratron, causing it to conduct on alternate half cycles. As in the thyratron switch, the plate relay contacts close and are maintained closed by C_2. The plate relay applies excitation to the thermistor bridge. The resistor R_1 limits current through the trigger during the initial breakdown of the thyratron.

The use of the resonant relay offers some promise for the application. The 1000 ohm coil version would yield a switch having high sensitivity with greater selectivity than attainable with a simple series resonant circuit. The use of the resonant relay eliminates 2 capacitors and the inductor as used in the thyratron switch.

The use of an additional relay could tend to reduce the reliability. Frahm claims a minimum life of 2×10^8 contact closure cycles. The contacts are not likely to wear out in this application but could be more subject to a catastrophic failure.

The advantages of the resonant relay approach appears sufficiently attractive to warrant further investigation to more thoroughly evaluate its possibilities. It would be potentially more useful at a lower frequency where it is difficult to obtain reasonably high Q in an inductor for use in a tuned circuit. The inherently higher Q of the resonant reed should result in a sensitivity greater than could be achieved with an L-C tuned circuit of reasonable size. The greater selectivity of the resonant relay would permit the use of control frequencies not far removed from the power line frequency.

CONCLUSIONS

The feasibility of using a 720 cps carrier voltage for remotely operating a small highly reliable accessory switch was established. The choice of 720 cps as the operating frequency is not necessarily optimum. It was found to be impractical to propagate a useful control signal through two distribution transformers at 720 cps. The use of a lower control frequency may produce more efficient propagation through two transformers. The use of 720 cps and a transmitter of reasonable power limits the use of the control to those circuits energized from a common transformer secondary. A further study is required to determine the optimum frequency.

Of the three types of switches developed, the thyratron with L-C tuning is the most promising. The mercury switch is impractical because of its fragility and position sensitivity. The resonant relay switch may have an advantage with lower frequency control signals. Both the thyratron and resonant relay switches could be made suitably small and would meet the requirements of the application. The reliability of the thyratron switch can be made adequately high, with that of the resonant reed relay closely approaching it.

A thermistor bridge was developed as part of the switch to provide transient immune, unambiguous self-synchronizing operation in response to time-duration coded control signals. As a result the condition of the switch can be relied upon without the need of repeat-back information.

A reasonably secure mode of operation is attained. The switch consumes no power in its standby condition and cannot be detected by watt-hour meter observations. Detection of the switch by electrical measurements is difficult because of the high impedance it presents when connected across the line.

RECOMMENDATIONS FOR FUTURE WORK

The following are areas in which additional future work is indicated to complete the development of the system and its components:

1. OPERATING FREQUENCY:

   Further study and tests are necessary to determine the optimum frequency. Effort should first be directed toward a lower frequency in an attempt to obtain propagation through two transformers. If this is demonstrated as impractical, a higher frequency should be explored as a means of reducing propagation losses, reducing transmitter size and power, and increasing switch sensitivity.

2. THERMISTOR BRIDGE

   The design of the bridge should be evaluated, preferably with an analog computer simulation, and optimized. The effects of ambient temperature on the bridge operation should also be evaluated.

3. TRANSMITTER

   An optimum transmitter should be developed, the design of which is contingent upon the results of item 1 above. Transmitter coupling networks must also be evaluated.

4. SWITCH

   The switch should be redesigned with a view toward full miniaturization. The usefulness of the resonant relay should be evaluated if the optimum frequency is low. Tests should be made to establish the effective reliability level of the switch.

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